Evaluation and Enhancement of IEEE 802.11p Standard: A Survey

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Abstract

VANETs are becoming more and more popular as a way to increase the traffic safety and comfort. The 802.11p standard has attracted much attention as part of the WAVE protocol in VANETs. Recently, many evaluations and enhancements have been proposed for the 802.11p standard. In this paper, the existing evaluations and enhancements of the 802.11p standard are first presented and classified. Subsequently, the present situations of the 802.11p standard are furthermore summarised based on the existing research works. Finally, five suggested research directions are proposed: (i) throughput improvement, (ii) scheduling optimisation, (iii) traffic control, (iv) channel estimation and equalisation, and (v) mobility affection.

Keywords

802.11p; Collision; Enhancement; Evaluation; Scheduling; Throughput; Traffic Control; VANETs; WAVE

Introduction

Vehicular ad-hoc Networks (VANETs) have attracted much attention owing to our society transportation problems such as traffic congestion, traffic accidents, lack of mobility and accessibility etc. During the last two decades, several technical groups such as the IEEE 1609 working group (1), the IEEE 802.11p task group (2), the ISO TC204 Working Group 16 (3) and the ETSI (4) ITS Technical Committee, were created in an attempt to solve the said problems. From that perspective, three main categories of applications are targeted: (i) road safety, (ii) traffic efficiency, and (iii) value added applications. VANETs constitute the cornerstone of the envisioned Intelligent Transportation Systems (ITS). By enabling vehicles to communicate with each other via Inter-Vehicle Communication (IVC), alternatively known as Vehicle to Vehicle (V2V), as well as with roadside base stations via Roadside-to-Vehicle Communication (RVC), also known as Vehicle to Infrastructure (V2I), VANETs will contribute to safer and more efficient roads by providing timely information to drivers and the authorities concerned.

VANETs present a challenging environment for protocol and application design due to their low latency and high data rate requirements in a high mobility environment. The IEEE 1609 working group has defined the first version of the protocol stack IEEE 802.11p/1609.x protocol families (5), also known as WAVE (Wireless Access in a Vehicular Environment). The WAVE protocols are designed for the 5.850-5.925 GHz band, the Dedicated Short Range Communications (DSRC) spectrum band in the United States (US), known as intelligent transportation systems radio service (ITS-RS). This 75 MHz band is divided into one central control channel (CCH) and six service channels (SCH) as depicted in Fig. 1. An overview of the WAVE protocol families is illustrated in Fig. 2. The IEEE 802.11p standard (2) defines the physical (PHY) and medium access control (MAC) layers based on earlier standards for Wireless LANs (Local Area Networks). The IEEE 802.11p uses the enhanced distributed channel access (EDCA) MAC sub-layer protocol designed based on the IEEE 802.11e with some modifications, while the physical layer is OFDM (Orthogonal Frequency Division Modulation) as used in IEEE 802.11a.

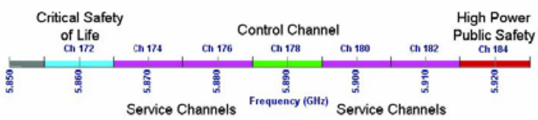

FIG.1 THE SET OF CHANNELS DEFINED IN THE WAVE TRIAL STANDARD (6)

The 802.11p standard has attracted much attention from researchers, while, recently many evaluations and enhancements were proposed for the 802.11p standard. However, the 802.11p standard is still a new and draft standard, and therefore certain problems still exist. Hence, the existing evaluations and

enhancements need to be classified and analysed in order to determine the unresolved problems and future research directions. In our previous work (8), the MAC protocol of 802.11p is surveyed. This paper is a extension work. In this work, in order to analysis the full stack of 802.11p protocol, the PHY protocol of 802.11p is included. Furthermore, more references for the MAC protocol are also identified and discussed. The main purpose of our paper is to survey the existing evaluations and enhancements of the 802.11p standard, and furthermore give out the present situation and future research directions of 802.11p.

The rest of this paper is organised as follows. In Section 2, the related work is presented. The overview of the 802.11p standard is described in Section 3. The existing evaluations and enhancements of the 802.11p standard are covered in Sections 4 and 5 respectively. The present situations and future research directions of the 802.11p standard are identified in Section 6. Finally, the conclusions are given in Section 7.

Related Work

In (9), a fairly detailed tutorial, in which the DSRC components and WAVE basic architecture were first discussed, the WAVE standards are presented. Subsequently, the details of WAVE MAC services and services management are also presented and explained. In addition, certain shortcomings of the current standard are indicated and some future research is identified. This paper is helpful for readers to understand the WAVE standards suite, especially regarding the WAVE MAC services and services management, which are explained completely and clearly. In (10), the challenges and perspectives of VANETs, their characteristics, the existing protocols, especially the routing protocols and future perspectives are presented. An overview of scheduling algorithms in wireless multimedia networks is furnished in (11), with the focusing falling on the scheduling algorithms for CDMA (Code Division Multiple Access), TDMA (Time Division Multiple Access) and multi-hop networks. In (12), some basic characteristics of vehicular networks such as the applications, challenges and solutions, some important ITS programs and projects are well discussed. However, none of the above mentioned sources focus on the detail of the IEEE 802.11p standard. In our previous work (8), only the MAC protocol of 802.11p is surveyed. To the best of our knowledge, no survey focusing on the full stack of IEEE 802.11p standard has been conducted to date.

Overview of 802.11p

In this section an overview of the IEEE 802.11p standard is presented, in which just the information required to give sense to following discussion is provided. Further information can be found in (2) and (6).

In 2004, IEEE 802.11 standard group migrated IEEE 802.11a for low overhead operations in the DSRC spectrum. Within IEEE 802.11, DSRC is known as IEEE 802.11p WAVE. The latest version of the IEEE 802.11p standard (2) was approved by IEEE on 17 June 2010. The 802.11p is strictly a MAC and PHY level standard. All knowledge and complexities related to the DSRC channel plan and operational concept are taken care of by the upper layer IEEE 1609 standards as shown in Fig. 2.

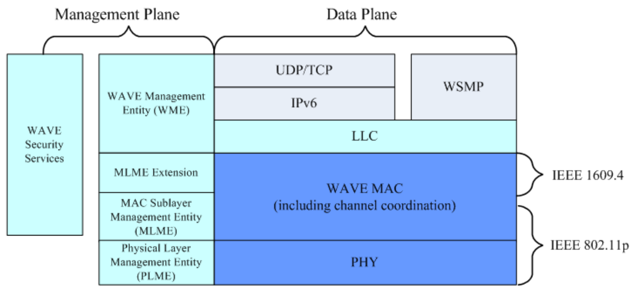

FIG. 2 THE WAVE PROTOCOL SUIT [7]

The IEEE 802.11p employs HCF (Hybrid coordination function) contention-based channel access EDCA (Enhanced Distributed Channel Access) as the MAC method, which is an enhanced version of the distributed coordination function (DCF) of 802.11. EDCA uses Carrier Sense Multiple Access (CSMA) with collision avoidance (CSMA/CA). The basic EDCA access method is depicted in Fig. 3. In EDCA scheme, a node willing to transmit will sense the medium, and if the medium is idle for greater than or equal to a AIFS[AC] (Arbitration Inter-Frame Space [Access Class]) period, the node starts transmitting directly. If the channel becomes busy during the AIFS[AC], the node will defer the transmission by selecting a random backoff time. The backoff procedure in EDCA functions is as follows: (i) The node selects a backoff time uniformly from the interval [0, CW[AC]] where the initial CW[AC] (Contention Window) value equals CWmin[AC]. (ii) The interval size will increase (double), if the subsequent transmission attempt fails, until the CW[AC] value equals CWmax[AC]. (iii) If no medium activity is indicated for the duration of a particular backoff slot, then the backoff procedure shall decrement its backoff time by aSlotTime. If the

medium is determined to be busy at any time during a backoff slot, then the backoff procedure is suspended. The medium shall be determined to be idle for the duration of AIFS[AC], before the backoff procedure is allowed to resume. (iv) When reaching a backoff value of 0, if the medium is sensed to be idle, the node will send immediately; If the medium becomes busy, the node will go to backoff again.

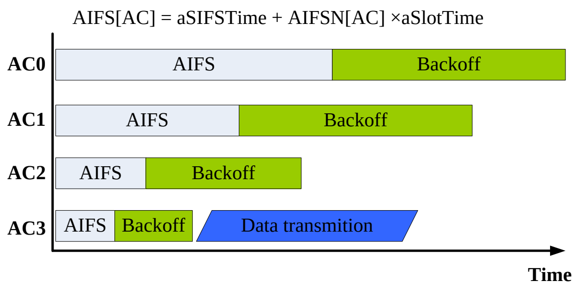

FIG. 3: A BASIC EDCA ACCESS SCHEME

However, in this scenario, the value of the CW[AC] is left unchanged. In order to ensure that highly relevant safety messages can be exchanged timeously and reliably, even when operating in a dense scenario, the 802.11p MAC protocol accounts for the priority of the messages using different Access Classes (ACs). There are four available data traffic categories with different priorities: background traffic (BK or AC0), best effort traffic (BE or AC1), video traffic (VI or AC2) and voice traffic (VO or AC3). A set of distinct channel access parameters, including AIFSN (Arbitration Inter-Frame Space Number) and CW, are selected for different ACs, as illustrated in Tab.1. A basic EDCA access scheme is illustrated in Fig. 3, where SIFS means the short inter frame space (SIFS). Each AC has a queue where messages are queued based on their priorities. If packets from different queues in the same station contend for the access, the message with higher priority will get more opportunity to access the channel due to the small value of AIFSN and CW.

TABLE 1 PARAMETER SETTINGS FOR DIFFERENT APPLICATION CATEGORIES IN IEEE 802.11P (2)

AC	CWmin	CWmax	AIFSN
BK	15	1023	9
BE	15	1023	6
VI	7	15	3
VO	3	7	2

The physical layer of the 802.11p is a variation of the OFDM based IEEE 802.11a standard. The IEEE 802.11p PHY employs 64-subcarrier OFDM, of which 52 are used for actual transmission, consisting of 48 data subcarriers and 4 pilot subcarriers. The pilot signals are used for tracing the frequency offset and phase noise. In order to reduce the effects of Doppler spread, the use of 10 MHz channels is adopted instead of the usual 20 MHz used by 802.11a. Consequently, all OFDM timing parameters are doubled (e.g. the guard interval, the OFDM symbol duration, etc.) and the data rates are halved (varying from 3 to 27 Mbps instead of 6 to 54 Mbps). The frequency is allocated at 5.850-5.925 GHz as displayed in Fig.1, which is divided into seven 10 MHz channels and a safety margin of 5 MHz at the lower end of the band. The centre channel is the control channel, which is reserved for system control and safety messages delivery. The remaining six channels are used as service channels, where lower priority communication is conducted after negotiation on the control channel. According to the IEEE 1609.4 coordination scheme (7), as shown in Fig. 4, the channel time is divided into synchronization intervals with a fixed length of 100*ms*, consisting of 50*ms* (including 5*ms* guard interval) alternating CCH and SCH intervals. All vehicles stay in the control channel during the CCH period and switch to one of the six service channels during the SCH interval. In addition, depending on the data rate that can be supported by channel conditions, four complex modulation methods (BPSK, QPSK, 16QAM, and 64QAM) are employed in the physical layer of the 802.11p. The default modulation parameters of PHY in 802.11p are illustrated in Table 2.

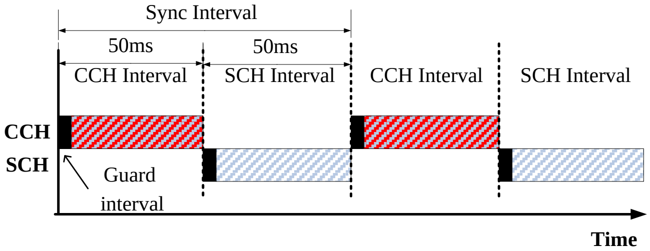

FIG. 4 CHANNEL INTERVAL

TABLE 2 PARAMETER SETTINGS OF PHY IN IEEE 802.11P (13)

Modulation	Coding rate (R)	Data rate (Mb/s)
BPSK	1/2	3
BPSK	3/4	4.5
QPSK	1/2	6
QPSK	3/4	9
16-QAM	1/2	12
16-QAM	3/4	18
64-QAM	1/2	24
64-QAM	3/4	27

In WAVE, each vehicle is expected to join a WBSS (WAVE Basic Service Set), which is a unique identifier for each communication zone. Vehicles must associate with only one WBSS at a time. Due to the high mobility of vehicles in VANETs, 802.11p simplifies the procedure to setup a WBSS without active scanning, association, and authentication procedures. To establish a WBSS, a provider periodically broadcasts the WAVE Service Advertisement (WSA) on the CCH. WSA contains the necessary information for the users to join the WBSS, such as the WBSS identifier, the availability of a service, the selected SCH, synchronization timing information etc. In the meantime, all the vehicles have to listen to the CCH during the CCH intervals. Thereafter, a user learns about available WBSSs and joins the WBSS which provides the services that the user is interested in by simply switching to the advertised SCH during SCH intervals.

Evaluations of 802.11p

In this section, the existing evaluations of this standard are presented and discussed. The existing evaluations can be divided into three categories according to the evaluation method: (i) Analysis-based evaluation, (ii) Simulation-based evaluation and (iii) Test-based evaluation.

Analysis-based Evaluation

In analysis-based evaluation, only the analytical models that can be used to analyse the performance of the 802.11p protocol for the different network environments are presented.

Certain analytical evaluation models are proposed based on Markov chains in (14) (15) (16) (17) (18) (19). In (14), an analytical model is proposed to compute the successful reception rate, collision probability and throughput of IEEE 802.11p within VANETs safety applications. The proposed model is based on a highway scenario on which the vehicles send status and emergency packets according to a Poisson distribution. In this model, two one-dimensional Markov chains are proposed to calculate the transmission probabilities of both the status and emergency packets. Subsequently, the recommended maximum range R=200m is derived from this model, which can be used to keep the delay as short as possible while achieving maximum throughput. In this model, two specified class AC3 and AC0 are considered for broadcast emergency and status packets. However, in the backoff process computation, a wrong parameter of DIFS is used which should be AIFS[AC]. In (15) and (16), a two-dimensional novel Markov chain analytical model for the 802.11p is proposed, which takes AIFS, CW for different ACs (AC0-AC3), while the internal collisions inside each station are accounted for. This analytical model is used to investigate the performance of the IEEE 802.11p MAC sub-layer in terms of throughput. However, it is analysed in a saturated scenario which does not model a realistic network. In (17), a discrete-time Markov chain based model is proposed for the EDCA MAC protocol, which considers the specific conditions of the control channel of a WAVE environment. The proposed model captures the fact that EDCA can establish priorities among the stations. The important metrics of QoS, such as throughput, losses, buffer occupancy and delays, are presented and analysed in this paper. However, the fact that the packet could go to backoff many times is not considered. As a result, the delay obtained in (17) is not accurate and a little shorter than the real value. In (18), the authors propose an analytic model for safety message delivery when using the channel coordination mechanism defined in the 802.11p standard. The 802.11p standard is evaluated based on both heavy traffic and light traffic conditions. The evaluation results derived from the proposed model indicate that the 802.11p standard can satisfy the needed latency requirements (less than 100ms), but cannot satisfy the required reliability for the safety message delivery (greater than 99.9%). However, the heavy traffic conditions which contain only 26 nodes are not explained clearly in the paper and hence the evaluation results based on the heavy traffic conditions are questionable. In (19), an analytical framework is proposed to analyse the performance of periodic broadcasting on the CCH in 802.11p vehicular networks. The effects of different EDCA parameter sets on network performance are analysed under various traffic load, error-prone channel, frame sizes, and transmission data rates. The analytical mode is simulated under MATLAB. The results show that increasing the window size or decreasing the frame's size can increase the transmission reliability.

The effect of time allocations on CCH and SCH in IEEE 802.11p are analysed in (20) (21) and (18). In (20), the effect is analysed while the CCH/SCH duty cycle is changing, the results obtained show that performance on CCH and SCH change significantly following the changing of the CCH/SCH duty cycle. It is shown that

CCH can accommodate around 80 users with best effort (AC1) and 80 users with background traffic (AC0) when the interval of CCH is set as 9*ms*, and it can accommodate 124 users for each of two background/best effort classes while when the interval of CCH is set as 45*ms*. However, the effect is not analysed when the interval of CCH is greater than 45*ms*. The authors continue their research in (21), the trade-off between CCH and SCH cycle is also analysed. As stated by the authors that the SCH service, which carries commercial infotainment applications, is focused in this paper. In (18), it is indicated that the 50*ms* CCH/SCH duty cycle value defined in the 802.11p standard is a good choice, since increasing the CCH interval value more than 50*ms* does not improve the performance on the CCH. However, as mentioned before, the heavy traffic conditions which contain only 26 nodes are not explained clearly in the paper and hence the evaluation results based on the heavy traffic conditions are questionable and unreliable.

In (22), a Packet Error Rate (PER) analytical model is proposed for 802.11p receivers to analysis the decoding process at the receiver. Most of the analytical models for 802.11p focus on the collision probability, the FER is neglected. The proposed FER analytical model describes the PER as the metric of a stochastic process depending on SNR, line-rate and packet length, which is suitable to be adopted by simulators in order to give a more accurate simulation result.

In analysis-based evaluations, MARKOV chain is the most popular metric to analysis the performance of the IEEE 802.11p. The CCH and SCH cycle is another famous research topic which attracts many attentions. In analytical model, the packet size of safety messages, which could affect the evaluation accuracy, should also be well considered in the analytical model. However, the packet size is set as 250, 500, and 1000 *byte* in (14), 512 *byte* in (15) and (17), 200 *byte* in (18) and (16). As defined in (23), the message size for the BSM (Basic Safety Message) part I is 39 *byte* and for the Part II, the VehicleSafetyExtension frame of the BSM which is less than 100 *byte*. Hence, the packet size of safety message should be 39 *byte* for a simple BSM (only part I) or 140 *byte* for an extended BSM (part I and part II).

Simulation-based Evaluation

Certain simulation-based evaluations are proposed in (24) (25) (26) (27) to evaluate the 802.11p standard based on different simulation models and scenarios. In (24), the authors present a model to analyse the characteristics and performance of C2C communication in urban environments. In the proposed model, it is assumed that the intervals of CCH and SCHs are equal and all the moving cars have information to transmit (only during SCH) in packets of 500 *bytes*. Subsequently, the model is simulated in a city scenario comprising an area of l*km* x l*km* and 100 blocks. The simulation results reveal that IEEE 802.11p technology is adequate as long as the number of cars remains small (< 100 cars in the simulation area). As the number of cars increases, (500, normal traffic flow), the number of contention cases also increases. With a dense traffic flow (>1000 cars), the results are drastically degraded, even with the use of the EDCA mechanism. However, the simulation scenario does not consider the road safety applications during CCH, which are more critical and important in VANETs. Furthermore, the radio range affects the contention significantly and which is set as 250*m* in the simulation. Hence, the number of contention could be higher than the results obtained in this paper in a highway scenario since the expected radio range for highway is up to 1000*m* (28). In (25), the IEEE 1609 WAVE and 802.11p standards are evaluated under three distinct simulation scenarios. The first one is a flat open air environment with a number of static vehicles. The second is an urban one corresponding to a region within Washington D.C., a digital form of the corresponding road network, while the third scenario corresponds to a roughly linear segment of a long highway, with a number of road side units (RSUs) placed at varying intervals to generate traffic towards the passing vehicles. Thereafter, three results are derived from the simulations: (i) control channel traffic, which can be successfully received even at a distance of 2.5*km* in an open air scenario with a 3*Mbps* data rate and 44.8*dBm* EIRP (Equivalent Isotropically Radiated Power); (ii) to ensure a moving vehicle can receive a steady data stream from the RSUs, the inter-RSU distance should fall in the range of 1000*m*-1500*m*; (iii) the delay on the control channel becomes longer than 100*ms* only when the total of the traffic offered approaches 1000 packets per second, which is too high for safety critical applications. Hence it is indicated in this paper that both WAVE and 802.11p appear to form a solid foundation for vehicular communication applications. In (26), the authors evaluate the IEEE 802.11p by considering collision probability, throughput and delay, by means of simulations and analysis. The simulation results indicate that the

average value of end-to-end delay for AC3 is 1*s* for 300 nodes with a total offered traffic of 3000 packets per second. However, the traffic threshold cannot be seen from the simulation results that when the delay is becoming longer than 100*ms*. And the delay for the scenario that the number of nodes is less than 150 is not presented well. In (27), the 802.11p standard is evaluated based on the ns-2 simulator. It is derived from simulation results that the aggregate throughput, average delay, and packet loss are not affected by the vehicle speed, but are significantly affected by the vehicle density. When the vehicle density increases, the aggregate throughput, and packet loss increases, and the average delay approach the asymptotic value of approximately 0.7286*ms*-0.7287*ms*. However, in this paper only a max of 196 vehicles are considered; herewith the network is not saturated. The average delay should also increase if the vehicle density increases till the network is overloaded.

Some evaluations, which are only for the physical layer of the 802.11p are also proposed in (29) (30) (31) (32). In (29), the physical layer is evaluated by using a realistic non-stationary vehicular channel model. Several channel estimators are simulated and compared in this work. Three kinds of estimators are defined based on the pilot structure, that is, block-based, comb-based and block-comb-based estimators. The simulation results indicate that the channel estimation performance is strongly influenced mainly by two factors: the strength of the diffuse components, and the SNR (Signal Noise Ratio). Whereas comb-based estimators perform best in environments with rich diffuse components and high SNR, block-based channel estimators perform well in the opposite case. Furthermore, in situations of a poor Line-of-Sight (LoS) contribution, an acceptable frame error rate is not achievable even at high SNR values. Therefore, it is indicated that more complex channel estimation and equalisation techniques based on the current standard pilot pattern need to be developed in order to cope with the properties of the vehicular radio channel. In (30), the authors present a realistic, yet computationally inexpensive simulation model for IEEE 802.11p radio shadowing in urban environments. The proposed model can accurately estimate the signal attenuation caused by buildings and other obstacles. It can also estimate realistic path loss values for ongoing radio communication very efficiently. The authors of (31) evaluate the PER (Packet Error Rate) performance degradation of the 802.11p PHY due to the time-varying channel and the Doppler Effect. A Matlab simulation model is developed and used to analyse the system performance in the context of high mobility. The simulation results show that the estimation process is the most affected by the rapid changes of the channel, severely affecting the PER performance (PER increases when the speed increases), while the ICI (Inter Carrier Interferences) have little or no impact on the performance at small data rates. It is also indicated that the use of two receiving antennas can significantly improve the PER. In (32), the maximum communication distance for IEEE 802.11p transceivers in a highway scenario is evaluated based on simulation. The simulation results indicate that the envisioned communication range of 1000*m* in the IEEE 802.11p project authorization request (PAR) cannot be reached with 2*W* EIRP and 3*Mbps* data rate in the investigated highway scenario. Of the successful communications, 90% are conducted at a distance of less than 750*m*.

In (33), 802.11p and WIMAX (Worldwide Interoperability for Microwave Access) technologies are compared in a high way scenario. Two scenarios to study the impacts of the source data rate and vehicle speed on 802.11p/WiMAX, are proposed. Subsequently, the coverage, average throughput, and end-to-end delay are evaluated for different vehicle speeds, traffic data rates, and network deployments. Finally, based on the simulation results, it is concluded that WiMAX offers large radio coverage and high data rates and that 802.11p is better suited to low traffic loads, where it offers very short latencies, even at high vehicle speeds. However, the simulation scenario presented in this paper only considers one vehicle; hence, the access collisions among the vehicles are not considered.

The simulation-based evaluation is one of the most efficiency and economic way to analysis the performance of the 802.11p in VANETs. The simulation parameter settings should be considered very carefully in order to give a realistic and accurate result. Some parameters such as the communication range, bitrate, transmission power are highly related to the application type. Regarding to the safety applications of DSRC, as defined in (34) and (35), the delay is required as 100*ms*, the expect communication range is from 100◎ 1000*m*. The WSM is sent on channel 172 using 6 *Mb/s* data rate. The maximum transmit power is defined as 800*mw* in (13), 760*mw* in (36).

Test-based Evaluation

In (37), the authors present an IEEE 802.11p full-stack prototype implementation of data exchange among and between vehicles and the roadway infrastructures. Three scenarios are considered in this work: hard-brake, accident, and tolling services. The performance of the proposed prototype is tested under realistic urban and suburban driving conditions. The results derived from the test indicate that communication is possible with a low Frame Error Rate (FER) or Bit Error Rate (BER) at approximately 400*m* with 22*dBm* EIRP. It is also indicated in this paper that communication is possible at higher distances, approximately 1000*m* with the same EIRP of 22*dBm*. In addition, the best place for the location of antenna is also tested; the roof location is identified as the best place. However, the OFDM PHY layer is not implemented and a single BPSK modulation with 1 Mbps of data rate is used in that system. The modulation affects the communication range. Hence, the results obtained might be not very accurate.

The authors in (38) carried out an infrastructure-to-vehicle trial using an IEEE 802.11p prototype on a real highway-the A12 in Tyrol, Austria. This paper presents the results of the evaluation of the average downstream performance of the PHY. It is indicated that shadowing effects, mainly caused by trucks, lead to a strongly fluctuating performance of the link quality, especially for settings with long packet lengths and high vehicle speeds. The maximum achievable range obtained in this paper is approximately 700*m* with 3*Mbps* data rate and 15.5*dBm* EIRP, where the frame-success-ratio is continuously larger than 0.25. The maximum data volume that can be transmitted when a vehicle driven by a roadside unit is achieved at low data rates of 6 and 9*Mbit/s*.

In (39), the reliability of 802.11p is analysed using real-world application data traffic, collected from three vehicles communicating with each other under both an open field traffic environment and a freeway traffic environment on a highway in the US. The reliability is analysed based on the metrics of the packet delivery ratio and the distribution of consecutive packet drops. The experimental data indicates that 802.11p provides an adequate degree of communication reliability under both traffic environments, and that the packet drops do not occur in bursts, even in the harsh freeway traffic environment. However, while this scenario only considers three vehicles, the reliability of 802.11p under a high data traffic environment is not evaluated.

In (40), the authors evaluate and discuss the required SNR for the specific FER threshold of 0.1 from IEEE 802.11p PHY performance measurements, carried out on an Austrian highway. The required SNR for achieving a FER less than 0.1 is estimated for various configurations of data rate, packet length, and vehicle speed. Two measurement scenarios are considered in this work: Low RSU and High RSU. Comparing the high RSU and the low RSU, the required SNR is always smaller in the case of the high RSU, with a mean difference over all parameter settings of 4.6 dB. In addition, considering the LoS between the RSU and the OBU (On Board Unit), it is strongly recommended that the position of the RSU antenna should be higher than the tallest of the vehicles.

Test-based evaluation can give a realistic evaluation result in terms of communication range, SNR and signal block. However, due to the high cost of test environment, some key metrics of QoS such as collision, throughput are not easy to be evaluated via test-based evaluation method.

Enhancements of 802.11p

In the previous section, the existing evaluations of the 802.11p standard are presented, and the performance of 802.11p is discussed and analysed. In this section, the existing enhancements of the 802.11p standard will be surveyed and discussed for the MAC and the PHY layers respectively.

Enhancements of MAC

Certain algorithms to improve the throughput of 802.11p standard are proposed in (41) (42) and (43). In (41), it is indicated that the MAC parameters for the original IEEE 802.11p MAC protocol can lead to undesired throughput performance because the backoff window sizes are not adaptive to the dynamics in the numbers of vehicles attempting to communicate. Thereafter, in this paper, two algorithms are proposed to address this problem. The first is named the Centralized Enhancement Algorithm (CEA) in which the exact information about the number of concurrent transmitting vehicles is used to calculate the optimal window size. However, the exact number of concurrent transmitting vehicles is difficult to obtain in the real network. Subsequently, the authors propose a Distributed Enhancement Algorithm (DEA) which estimates the number of

concurrent transmitting vehicles and adapts the window size. The simulation results indicate that the proposed DEA can improve the throughput of the network from 7% to 79% for different networks. However, the estimation of the number of concurrent transmitting vehicles is not very accurate and hence the gain of throughput is not stable for different networks. In (42), the authors propose a Vehicular Channel Access Scheme (VCAS) to optimise the channel throughput. In the VCAS, all OBUs have to listen to CCH for receiving WAVE announcement frames, which carry WSA information and are broadcast by RSU during CCH intervals. Thereafter, a number of OBUs with similar transmission rates are grouped into one SCH by using the transmission distance threshold carried by the WSA frame. The group sizes of channels are controlled in order to fulfil the fairness requirement. In order to flexibly compromise the trade-off between throughput and fairness, a marginal utility model is proposed. Simulation results demonstrate that the proposed VCAS with marginal utility provides a flexible method to handle versatile vehicular scenarios. However, VCAS requires that RSU has two or more transceivers, which might not be suited to certain environments. A Detection-Based MAC protocol is presented in (43), in which RTS/CTS (Request To Send/Clear To Send) is used to detect network congestion through message exchange and to predict the number of competing nodes. Subsequently, the nodes dynamically adapt the contention window size based on the network status detection and the prediction of the competing nodes. The proposed Detection-Based MAC outperforms the IEEE 802.11 Base Access and RTS/CTS in total throughput by plus 50.4% and 62.6%, respectively; and the collision rate by 48.8% and 10.6% less, respectively. Besides, it is proved that Detection-Based MAC has the least standard deviation of delay. However, it is not explained clearly in this paper how the nodes guarantee that the predicted number of competing nodes is accurate.

In (44) (45) (46), some enhanced algorithms are proposed for the service channels. In (44), a cooperative reservation scheme for service channels in the VANETs named CRaSCH (Cooperative Reservation of SCH) is proposed. The main idea of CRaSCH is to exploit, as much as possible, the WSA frames sent on the CCH interval to spread out information regarding the SCH occupancy among 1-hop and 2-hop neighbouring providers, in order to ensure the set up of channel-disjoint WBSSs. Two approaches: Proactive Gossiping and Reactive Gossiping are proposed in CRaSCH to reduce the cases where two or more providers choose the same service channel for non-safety traffic delivery. Simulation results show that CRaSCH outperforms 802.11p in both highway and urban scenarios with only a few additional bytes overhead. In (45), the authors propose an improved channel access scheme in order to allow a station to stay on a service channel for as long as it requires before returning to the control channel. The main idea of this algorithm is to cut off CCH in order to extend SCH and hence to improve the service channel utilisation. However, in vehicular networks the safety messages, which are transmitted during CCH, enjoy a higher priority; hence the CCH interval must be guaranteed. In addition, one user only is considered in this paper and the effects incurred by changing channel intervals to its neighbours are not analysed. In (46) a WAVE-based Hybrid Coordination Function (W-HCF) protocol is proposed to leverage controlled access capabilities on top of the basic contention-based access of the IEEE 802.11p. The W-HCF scheme relies on alternate centralised and distributed channel access over SCHs, in order to satisfy the requirements of QoS-sensitive infotainment applications, while still keeping bandwidth available for non QoS-sensitive services. The main idea of W-HCF is to reserve part of the SCHs intervals for QoS-sensitive applications in which the access control is centralised. The remaining parts of intervals are for non QoS-sensitive applications in which the access control is distributed and contention-based. The W-HCF can offer a stable performance with meeting both the time delivery constraints and goodput requirements of non-safety infotainment applications regardless the traffic load. However some extra signalling is required by W-HCF for resource reservation and polling which consequently increase the traffic load. Furthermore, the end-to-end delay could be prolonged by W-HCF due to the centralised access control proceeding when the traffic load is low.

Some collision avoidance algorithms are proposed in (47) (48) (49) in order to reduce the collision rate in 802.11p. A solicitation-based IEEE 802.11p operation mode called WBSS User Initiation Mode (W-UIM) is proposed in (47) to avoid packet collisions by using a polling scheme. In W-UIM, a WBSS user solicits data frames destined for itself in an opportunistic manner, by requesting the transmissions of the frames from a WBSS provider by a WAVE-poll frame. Throughput analysis proposed in this paper reveals that W-UIM

achieves a stable saturated WBSS throughput which is higher than IEEE 802.11 irrespective of the number of contending and moving-away WBSS users. However, the analysis is only based on a theoretical calculation and is not verified by simulation or realistic experiment. Furthermore, the analysis method is not presented completely and clearly. In (48) the Coupon Collector's Problem (50) in the IEEE 802.11p MAC is presented. It is indicated that much time for collecting all vehicle information is needed owing to the randomness of the channel access in the IEEE 802.11p MAC and the unreliable nature of the safety beacon broadcast. Therefore, the authors propose a solution approach to the Coupon Collector's Problem which suppresses the WAVE nodes that succeeded, in the previous attempt, in contending for the channel for the next few safety beacon intervals. However in this algorithm, the application level feedback is used and transmitted in order to let the successful nodes know that they have succeeded, which consequently increases the network traffic. Furthermore, the safety beacon is time critical; hence the suppression of the safety beacon may not be suited to the vehicular networks. In (49), a strict priorities algorithm for 802.11p MAC protocol is proposed. The main idea of the proposed algorithm is to prolong the AIFS of the lower-priority frames in order to reduce the higher-priority frames contention and furthermore improve the performance of higher-priority frames. The proposed AIFS is determined as $AIFS_{Lower}=AIFS_{Higer}+CWmax_{Higher}$. The simulation results indicate that the proposed algorithm is effective in reducing delay, jitter and losses for the most critical messages, even in high-traffic conditions. The price to pay here is an increase in the delay experienced by lower-priority frames.

In 51) a variable CCH interval (VCI) multichannel MAC Scheme is proposed. The VCI MAC scheme adopts a new coordination mechanism to provide contention-free SCHs by a channel reservation on CCH. However, the CCH interval reserved for safety message delivery is not calculated well. Firstly, in VCI MAC scheme, only the safety message transmission time is counted in the CCH interval calculation. The backoff time should be counted and hence the time duration needed by the safety message delivery should be much longer than the result obtained in (51). Secondly, the safety message frequency is considered as 2 per second which is too low to meet the safety application requirement. In addition, in the analytical model only the saturation scenario is considered, which does not suit to the realistic network environment.

In (52), a Self-organizing Time Division Multiple Access (STDMA) for real-time data traffic between vehicles is proposed. In STDMA the time is divided into frames as in a TDMA system and all vehicles strive for a common frame start. These frames, which are one second long in this study, are further divided into slots, which typically correspond to the duration of one packet. Subsequently, each vehicle selects proper slots after four different phases: *initialisation*, *network entry*, *first frame*, and *continuous operation*. STDMA attempts to ensure that each vehicle can access the channel regardless of the number of competing nodes. It has been demonstrated via simulation that STDMA performs better than CSMA under the periodic vehicle to vehicle broadcasting scenario. Thereafter, CSMA and STDMA in (53) are compared for broadcasting periodic position messages in a realistic highway scenario. The scalability in terms of the number of vehicles that the VANET can support using metrics, such as channel access delay, probability of concurrent transmissions and interference distance, is investigated. It is concluded in (53) that the main difference between the MAC methods CSMA and STDMA occurs where concurrent transmissions take place in space. In CSMA, it is randomly distributed, whereas in STDMA it is scheduled using the side information from the position messages. Therefore, when the network load in a VANET increases, STDMA becomes increasingly more attractive compared to CSMA. STDMA may also provide increased reliability due to reduced interference for nodes situated closest to the current transmitters. STDMA provides fairness, predictable channel access delay, and good scalability since all channel requests turn into channel access, which are scheduled far apart in space. However, as indicated in (54) with respect to high vehicular mobility, this renders makes MAC coordination very difficult; hence the performance of STDMA needs further evaluation, especially with regards to the coordination issue.

In (55), the unfairness problem due to the relative speed among vehicles is identified. It is indicated that the vehicle with higher speed has less opportunity to access a channel due to the short travel time in the communication range. Two priority channel access schemes based on vehicle mobility are then proposed to address the unfairness problem. In the proposed schemes, the vehicle with higher speed or lower transmission probability has a higher priority to access

the channel. The proposed schemes are proved to be able to provide better fairness and performance in certain scenarios. However, the priority adaption could affect the performance of high priority data. The higher priority data are normally very critical to the delivery reliability and transmission delay. As a result, the affection to the performance of higher priority data should be well considered.

It can be seen from the recent enhancements of 802.1p MAC that the network throughput and collision avoidance are focused recently. Many researchers show more interest on the SCH channel. As a result, the CCH channel needs more attention since the safety related messages, which are very critical to the reliability and delay, are transmitted on CCH.

Enhancements of PHY

Compared to the MAC, PHY has fewer enhancements. The algorithms proposed in (56) and (57) address the channel estimation and equalisation problem. In (56), the authors indicate that a narrow coherence bandwidth and short coherence time contribute to a degraded physical layer performance in V2V channels. The traditional, preamble based equalisation scheme adapted by 802.11p is insufficient for combating the V2V channel effects. Subsequently, four equalisation schemes: Comb Pilot Interpolation, Comb Co-Pilot Interpolation, Constellation-Aware Data Equalisation, and Spectral Temporal Averaging, are proposed using the existing pilot subcarriers or using the pilot subcarriers in combination with data subcarriers. The proposed schemes were tested on real V2V waveforms and indicated that adding greater reliance on data to aid in channel estimation improves the packet error rate. The experiment data also indicate that the spectral temporal averaging outperforms the other proposed schemes, and decreases PER significantly. Additionally, these equalisation methods are receiver-centric and will not require a change to the 802.11p standard. In (57), the performances of V2X (vehicle-to-anything) communications based on the IEEE 802.11p WAVE system are investigated in practical small-scale fading models re-designed for computer simulations. The problem of the conventional least squares (LS) channel estimator using two long training symbols adopted by 802.11p is addressed, and an enhanced linear minimum mean square error smoothing-aided decision directed (LSA-DD) channel estimator is proposed to track the time variation of fading channels and mitigate noise enhancement. However, the proposed LSA-DD is only compared with LS in the worst channel in which the PER is always 1 for LS; hence the evaluation is not comprehensive.

In (58), the performance of IEEE 802.11p PHY employing turbo coding is evaluated based on Matlab simulation and FPGA (Field Programmable Gate Array) implementation. The BER vs. SNR for different kinds of modulation schemes in different channels is simulated. Compared to other techniques, the turbo coding scheme achieves a significant improvement in the performance of 802.11p, while the turbo coding gain can reach up to $6dB$, and the resource overhead is always below 10%.

In (58), the performance of spatial diversity for broadcast safety applications in a V2V environment is presented. The performances of MIMO-STBC (Multi-Input Multi-Output Space-Time Block Coding) and SISO (Single Input Single output) systems are compared. It is demonstrated that MIMO-STBC offers a 43% to 80% range extension as compared to a SISO system. However, more antennas are consequently needed in MIMO-STBC.

Present Situations and Future Research Directions of 802.11p

In the previous two sections, the evaluations and the enhancements of the 802.11p standard are presented and discussed. In this section, the present situations of the 802.11p standard, based on the previous discussions, are summarised. Subsequently, the future research directions of the 802.11p are identified.

Present Situations of 802.11p

The present situations of the 802.11p standard are concluded and presented in some important metrics, as indicated below:

TABLE 3 COMMUNICATION RANGE

SN	Communication Range(m)	FER	EIRP (dBm)	Data Rate (Mbps)	Evaluation Method	Reference
1	400	◎ 0.11	22	1	realistic experiment	(37)
2	1000	not evaluated	22	1	realistic experiment	(37)
3	700	◎ 0.75	15.5	3	realistic experiment	(38)
4	750	◎ 0.1	33	3	simulation	(32)
5	2500	not evaluated	44.8	3	simulation	(25)

1. Throughput: Four analytical models are proposed to analyse the throughput of 802.11p in (14) (15) (17) (20) respectively. All these models are based on Markov Chains. In order to improve the performance of 802.11p in terms of throughput, some enhanced MAC protocols, such as CEA and DEA in (41), the VCAS in (42) and the Detection-Based MAC in (43), are proposed. VCAS requires that RSU possesses two or more transceivers. The DEA and Detection-Based MAC use a similar concept: that the contention window size be adapted according to the network status. The main difference between DEA and Detection-Based MAC lies in how to detect the network status. However, the status of the network obtained by these two algorithms has not been very accurate so far.

2. Scheduling: The effect of changing the CCH/SCH duty cycle is analysed in (20) (21) (45) (51). In (20) and (21), the numbers of users on CCH and SCH are discussed when the CCH interval is from 9*ms* to 45*ms*. In (45), an algorithm is proposed to improve the SCH channel access scheme by cutting off CCH in order to extend SCH. The VCI MAC scheme in (51) adopts a new coordination mechanism to provide contention-free SCHs by a channel reservation on CCH. Hence all the proposed algorithms only improve the service channel utilisation without considering the control channel utilisation. The CRaSCH proposed in (44) can reduce the case where two or more near providers select the same service channel by adopting Proactive and Reactive Gossiping approaches. The W-HCF proposed in (46) offers a stable performance of non-safety infotainment applications regardless of the traffic load. However, some extra signalling is required by W-HCF for resource reservation and polling, which consequently increases the traffic load. In (19) and (55), the idea of adapting the EDCA parameter sets in order to improve the performance of 802.11p under some particular scenarios is proposed. The effects of the different EDCA parameter sets on network performance are analysed and discussed.

3. Collisions: Collision avoidance function is very important to the 802.11p standard since it can affect the QoS of VANETs significantly. It is demonstrated in (24) that the collision probability increases if traffic flow increases. Thereafter, four algorithms are proposed in order to reduce the collisions in VANETs. The Detection-Based MAC proposed in (43) can reduce the collision rate by adapting the contention window size based on the network status detection and the prediction of the competing nodes. In (48), a collision avoidance algorithm is proposed to address the Coupon Collector's problem by suppressing some nodes contending. The W-UIM proposed in (47) uses a polling scheme to avoid packet collisions. The strict priorities algorithm proposed in (49) can reduce the higher-priority frames collision by suppressing the lower-priority frames contention.

4. Latency: Due to the high mobility of vehicles, latency is a critical parameter for the designing of MAC protocol in VANETs. It is indicated in (33) that compared with WIMAX, 802.11p is better suited to low traffic loads, where it offers very short latencies even at high vehicle speed. However, the latency is affected by traffic significantly. In (25), it is concluded that only when the total amount of traffic offered approaches 1000 packets per second, does the delay on the control channel become longer than 100*ms*, which is too high for safety critical applications. In (26), it is indicated that the delay on the control channel is 1*s* with a total of offered traffic of 3000 packets per second.

5. Communication range: Four works have evaluated the communication range of 802.11p in (37) (38) (32) (25) respectively. The results obtained are shown in Table. 3. It can be observed that the communication range highly depends on the set of EIRP, FER and data rate. It can also be seen that 802.11p standard is adequate in terms of communication range (around 1000*m* expected in WAVE) with a proper set of EIRP and data rate. In (58), an enhanced algorithm MIMO-STBC is proposed, which offers an extension within the 43% to 80% range by employing more antennas, as compared to a SISO system.

6. Channel estimation and equalisation: Some channel estimation models are proposed in (29) (30) (31). In (29), several channel estimators are simulated and compared. Furthermore, it is indicated that in situations of poor LoS, 802.11p PHY does not perform well, even at high SNR values and hence more complex channel estimation and equalisation techniques need to be developed. The model proposed in (30) can accurately estimate the signal attenuation caused by buildings and other obstacles. The model proposed in (31) is designed for evaluating the PER performance degradation of the 802.11p PHY caused by the time-varying channel and the Doppler Effect. Some enhanced algorithms are proposed to address the channel estimation and equalisation problem in (56) and (57). In (56), four equalisation schemes are proposed and the spectral temporal averaging scheme

is demonstrated to be the best to decrease PER significantly. In (57), the LSA-DD channel estimator is proposed to track the time variation of fading channels and mitigate noise enhancement.

7. Mobility: The affections of high speed mobility in VANETs are evaluated in (27) (31) (55). In (27) it is proven that packet loss is not affected by the vehicle speed. However, in (31) an opposite result is obtained that PER increases when vehicle speed increases. In (55), the mobility affection is analysed in terms of channel access opportunity.

Future Research Directions of 802.11p

VANETs possess certain characteristics due to the high speed mobility of the vehicle, for example, rapid changes of topology, potentially large-scale, veritable network density and so forth (10). These characteristics indicate important implications for the design of protocol in VANETs. Based on the characteristics of VANETs and the present situation of the 802.11p standard, the suggested future research directions of the 802.11p standard are furnished as follows:

1. Throughput improvement: In VANETs, many safety messages need to be broadcast among vehicles periodically, while communication between vehicle and RSU is also needed in order to realise intelligent transport control. Hence, high throughput is required in VANETs. Due to the characteristics of VANETs, the network density and the topology of VANETs are not stable. Hence, an intelligent MAC protocol is needed that can dynamically adapt its parameters based on the network status in order to improve the network throughput. In (41) and (43), certain algorithms are proposed and further research is needed to improve the network detection algorithms.

2. Scheduling optimisation: The idea of adapting the intervals of CCH and SCH is proposed in (20) (21) (45) (51). The algorithm proposed in (45) can improve the channel utilisation when there are a greater number of services messages and fewer control messages. Due to the variable network density in VANETs, a scheduling optimisation algorithm is needed to adapt the intervals of CCH and SCH, depending on the network status. In addition, the network detection algorithms could also be adapted to detect the network status.

3. Traffic control: It is stated in (24) that the number of contention cases increases if the traffic flow increases. Contention incurs collisions; in other words, the number of collisions increases if the traffic flow increases. Hence, traffic control is the key to solving the collision problem in VANETs. Latency is very critical in VANETs due to the short time needed by a critical safety application. It is evident, when comparing the results of (25) and (26), that high traffic leads to longer periods of latency. Hence, traffic control is also the key to reducing latency in VANETs. Consequently, traffic control technology is needed to reduce collisions as well as latency in VANETs.

4. Channel estimation and equalisation: The poor LoS problem caused by building, tree or big truck, as indicated in (29) and (30), require more complex channel estimation and equalisation techniques with considering the characteristics of VANETs. In addition, as indicated in (56) and (57), enhanced channel estimation and equalisation techniques can improve the throughput of network by decreasing the PER and noise.

5. Mobility affection: High speed mobility is a basic characteristic of VANETs, and hence the affection of high speed mobility needs to be considered in the VANETs protocol design. However the existing evaluations proposed in (27) and (31) yield a conflictive result. Hence, further research needs to be carried out in terms of the mobility affection.

Conclusions

In this paper, most of the recent proposed evaluations and enhancements related to the 802.11p standard are covered. First of all, the evaluations of 802.11p are presented in three categories based on the simulation methods. Secondly, the enhancements of the 802.11p for MAC and PHY layer are discussed respectively. Based on the existing research works, the present situations of 802.11p standard are subsequently analysed followed by conclusions. Finally, five suggested research directions: (i) throughput improvement, (ii) scheduling optimisation, (iii) traffic control, (iv)channel estimation and equalisation, and (v) mobility affection, are proposed.

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